NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3585

DETERMINATION OF SURGE AND STALL LIMITS OF AN AXIAL-FLOW TURBOJET ENGINE FOR CONTROL APPLICATIONS

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SUMMARY

During the course of an investigation of an axial-flow turbojet engine in the Lewis altitude wind tunnel, limitations on the transient operation of the engine were determined in relation to two altitudes and exhaust-nozzle-areas. Below approximately 70 percent of the generalized engine rotational speed, a high-frequency oscillation (stall) at the compressor inlet limited transient operation of the engine. Over 70 percent of the engine speed, transient operation was limited by a low-frequency oscillation (surge), which occurred throughout the engine.

The data presented are the result of an analysis of oscillograph traces obtained when the engine was operated off steady state by introducing either a step increase or a ramp increase in fuel flow. For a given speed, a lower fuel flow was required for the engine to recover from surge or stall than was necessary for surge or stall to occur. Very little difference existed between the surge line (compressor pressure ratio against engine rotational speed) obtained under transient conditions and that obtained under steady-state conditions by decreasing the flow area with an adjustable first-stage turbine stator.

INTRODUCTION

The demand for greater acceleration performance of present-day turbojet engines has necessarily required that acceleration limitations be more precisely defined over the range of engine operating conditions. Also, the new high-pressure-ratio engines have steady-state operating lines which are proportionately closer to the surge limit in order to obtain high compressor pressure ratios at rated conditions. This reduces the acceleration potential of the engine, and therefore a thorough knowledge of transient operating characteristics becomes essential in order to utilize the full acceleration potential of the engine. Some engines have been found to possess good acceleration even though operating in surge.

[1]Supersedes recently declassified NACA Research Memorandum E53B10 by Ross D. Schmidt, George Vasu, and Edward W. McGraw, 1953.

However, consideration of blade stresses and high turbine temperatures that result from the large decrease in air flow and losses in compressor efficiency associated with surge generally imposes the surge line as an acceleration limit of engine transient performance.

Although the problem of surge in centrifugal compressors has been studied since superchargers were developed for reciprocating aircraft engines, little is known about the details of surge phenomena. Most of the surge investigations have been conducted on single-stage centrifugal and axial-flow compressors in an effort to simplify the prob- 2725
lem. The complexity of the flow dynamics in multistage compressors due to stage interaction greatly increases the difficulty of obtaining accurate surge data. Also, an analysis of the data becomes much more involved because of the increased amount of data necessarily required. Some of the work which has been done in studying the surge characteristics of single-stage and multistage axial-flow compressors is presented in reference 1.

Previous investigations have shown that recovery from surge, as indicated in a plot of compressor pressure ratio against engine rotational speed, occurs below the surge line and, in general, below the steady-state operating line. For this reason, the relation of the surge and stall lines and corresponding recovery lines with respect to other engine operating parameters was of particular interest in this investigation conducted at the NACA Lewis laboratory. The compressor surge and stall limits of a particular turbojet engine as related to the following engine parameters are presented herein: fuel flow, engine rotational speed, compressor pressure ratio, and compressor pressure rise. These parameters were determined for operation at two altitudes and two exhaust-nozzle areas at a constant flight Mach number. The frequency of surge and stall was also investigated, and the variation in frequency between the surge and stall regions is presented in relation to the engine parameters. A comparison of the surge line obtained by decreasing the flow area in the adjustable first-stage turbine stator so as to approach surge in a steady-state condition and the surge line obtained from transient data is also presented.

APPARATUS

Engine. - The turbojet engine consisted of an 11-stage axial-flow compressor with a divided inlet, a single annular combustor, a two-stage turbine, and a variable-area exhaust nozzle. A schematic diagram of the engine is presented in figure 1. (All symbols used in the figures are defined in appendix A.) Before the surge investigation, an adjustable first-stage turbine stator was installed to permit an approach to the compressor surge line in a steady-state manner by varying the turbine-inlet nozzle area.

Test equipment. - The engine was installed in the Lewis altitude wind tunnel. The entrance air duct for the engine consisted of a bell-mouth inlet followed by a split duct which admitted the air to the two elliptical compressor-inlet openings. A sketch of this inlet and the instrumentation stations throughout the engine are also shown in figure 1.

Instrumentation. - To obtain valid off-steady-state data requires the use of instrumentation that combines accuracy with good dynamic response. Therefore, careful consideration was given to transient instrumentation requirements. Engine parameters were recorded during transients on two six-channel, direct-writing oscillographs. The parameters recorded and the instrumentation used to measure values of the parameters in the steady state are summarized in table I. The sensing devices used to measure the variations in parameters during transients and the frequency response range of the transient instrumentation are also shown. A description of the transient instrumentation is given in appendix B.

Fuel system. - In order to maintain a constant engine fuel flow at any given operating condition, a fuel regulator and valve were designed and built at the Lewis laboratory. The fuel valve was designed to operate over a broad fuel-flow range as encountered in varying altitude conditions, and the pressure drop across the fuel valve was maintained constant by the fuel regulator. The rapid response of the fuel regulator reduced the random flow fluctuations and oscillations which normally occur in fuel systems. The fuel regulator also decreased the oscillations in fuel flow which occurred when a sudden change was made in the setting of the fuel valve. In order to approximate a step change in fuel flow as closely as possible, the fuel valve was actuated by a piston which was preloaded with compressed air. Upon release of a trigger mechanism, the fuel valve was impelled by the piston to the assigned position.

PROCEDURE

For the part of the investigation involving the determination of the surge and stall limits, the engine was operated at altitudes of 15,000 and 35,000 feet. The ram pressure ratio was held to a nominal value of 1.02 at both altitudes and showed very little variation during a transient except during a surge or a stall encounter.

The data to be presented were obtained from an analysis of the transient response of the engine to two types of fuel disturbance. As shown in figure 2, a step increase in fuel flow was made from a steady-state condition and the engine was allowed to accelerate to the final equilibrium rotational speed. The other type of fuel disturbance used was a ramp increase in fuel flow (shown in fig. 3). In both cases, transients were accomplished from a number of initial steady-state conditions using various size steps and ramp rates. After a step or a ramp increase in fuel flow had been made, it was necessary, in some cases, to reduce the fuel flow to prevent unsafe engine operation. 2725
During a step increase in fuel flow, the fuel flow changed so rapidly that there was difficulty in determining the value of fuel flow at which the engine surged; therefore, a number of fuel steps of increasing magnitude were made from the same initial engine rotational speed until surge was encountered. In this way a fuel-flow step just out of surge and a step just into the surge region yielded the approximate surge fuel flow. The ramp increase in fuel flow was then used in order to determine whether the surge limit was a function of the manner in which the surge limit was approached, and if not, to substantiate the data obtained using the step increases in fuel flow.

In order to establish the surge and stall lines from 40 to 90 percent of the rated engine rotational speed at each altitude, the transients were initiated at engine rotational speeds differing from each other by 5-percent increments.

The data traces for all parameters were calibrated by using steady-state readings taken at the beginning and the end of each run. After a number of transients were accomplished in this manner, an average calibration was obtained for each of the individual parameters recorded. The results of the transient-data analysis in which these calibrations were used are discussed in the following section.

RESULTS AND DISCUSSION

The results were obtained from an analysis of oscillographic traces similar to the ones shown in figures 2 and 3. A step disturbance was initiated in fuel flow, and the engine encountered stall shown by the high-frequency oscillation in ram pressure and inlet dynamic pressure and the drop in compressor-exit pressure (fig. 2). The point at which the engine encountered stall is labeled A in figure 2. The amplitude of the oscillations then increased with engine rotational speed as the fuel flow was held constant. Engine acceleration approached zero just before the fuel flow was reduced to enable the engine to recover from stall. The point at which the engine recovered from stall is labeled B in figure 2.

Figure 3 shows the result of a ramp increase in fuel flow. The engine encountered stall initially as shown by the high-frequency

oscillation. As the fuel flow was increased further, surge occurred as indicated on the trace of the compressor-exit pressure and the change in the character of the oscillations on the traces of the inlet dynamic pressure, ram pressure, and acceleration. Surge differs from stall in that the oscillations occur throughout the engine at a low frequency, while the high-frequency oscillations encountered in stall occur chiefly at the compressor inlet. If stall did occur at the compressor exit, the amplitude of the high-frequency oscillations was so
2725 small that the instrumentation was not sufficiently sensitive to determine such oscillations. The transition point at which the engine went from stall to surge, that is, from a high to a low frequency, is labeled C in figure 3. The engine then went on to recover from surge and the recovery point is labeled D in figure 3. The acceleration trace shows a large decrease in acceleration during stall, but during surge the acceleration increased to approximately three-fourths of the value obtained just before stall occurred.

Hysteresis. - The figures to be discussed in this section (figs. 4 to 8) were obtained from an analysis of the transient and steady-state data taken with the engine operating at an altitude of 15,000 feet, a ram pressure ratio of 1.02, and a ratio of exhaust-nozzle area to turbine-exit-annulus area of 1.1. The values of the various parameters used in the plots are expressed in terms of the percentage of the value at rated military static sea-level conditions.

Analysis of the transient data indicated that a lower fuel flow existed when the engine recovered from surge and stall than when the engine went into surge or stall at the same engine rotational speed. This hysteresis effect was evident over the entire engine-rotational-speed range.

Because most controls attempt to follow the stall and surge lines rather closely in order to obtain rapid acceleration, it is of considerable importance to examine the engine characteristics closely in the region near stall or surge. This is especially true where a hysteresis effect occurs because a hysteretic characteristic imposes additional requirements on a control. These requirements will be brought out in the discussion of figure 4.

The variation of fuel flow with engine speed presented in figure 4 illustrates the relation between the steady-state, surge, surge-recovery, stall, and stall-recovery lines. An inspection of the stall and surge and corresponding recovery lines reveals that below about 67-percent engine rotational speed, stall is encountered before the engine begins to surge. Above approximately 67-percent engine rotational speed, the engine goes directly into surge with an increase in fuel flow at constant speed. Below 67-percent speed, the fuel flow at which compressor stall occurred is essentially constant, but the fuel flow for compressor surge increases with decreasing engine speed. Above 70-percent speed, the fuel flow for compressor surge increases with increasing engine speed.

From figure 4 it may be seen that the hysteresis effect is present over the entire engine-rotational-speed range. At low speeds an increase in fuel flow drives the engine initially into a stalled region; with further increase in fuel flow, the engine enters a surge region. 2725
Above 70-percent engine speed, the engine enters a surge region immediately upon an increase in fuel flow. Conversely, at low speeds the fuel flow must be reduced below the surge line to recover from surge and return to a stalled condition and, furthermore, the fuel flow must be reduced well below the stall line to recover from the stalled condition. At the higher speeds (above approximately 70-percent engine speed), reducing the fuel flow to the surge-recovery line enables the engine to recover immediately without operating through a stalled region.

If the engine enters stall at low speeds and the fuel flow is held constant, a large speed range must be traversed in stall before recovery. Because acceleration in stall varies approximately from one-fourth to two-thirds of the acceleration just before stall (see acceleration traces in figs. 2 and 3), a long period of high-temperature operation would be encountered. The acceleration out of stall varies essentially linearly with fuel flow, and because the recovery line at low speed is approximately midway between the steady-state and stall lines, the recovery line represents an "out-of-stall" acceleration of one-half that obtained at the point just before stall is attained at the same engine rotational speed.

The stall-recovery line appears to terminate at approximately 76 percent of the engine rotational speed. From the data obtained in this region, it appears that the engine would not accelerate to recovery from stall if at low speeds the fuel flow were increased to the stall line and held constant. Under such conditions, as the engine rotational speed increases to approximately 75 percent, the acceleration approaches a negligible value, so that for all practical purposes, the engine will not recover from stall (fig. 2).

It is evident that such a stall region of essentially zero acceleration must be avoided. It must be remembered that small overshoots in fuel flow frequently occur that are difficult to eliminate under all conditions. In order definitely to avoid the stall regions it would therefore be necessary to provide an additional margin of safety to allow for any possible extraneous disturbances or to provide a control system where the fuel flow would be reduced below the recovery line in the event a stall occurred.

The data points in figure 4 consist of both step and ramp increases in fuel flow. In general, these two types of fuel disturbance appeared to yield the same results. At very low speeds, however, where it was possible to use only step increases in fuel flow to determine the stall line, it was found that the fuel flow could have a large overshoot and stall would not be encountered until shortly after the final fuel flow was attained (see fig. 2). This was probably the result of poor combustion efficiency in this region of low speed and high fuel flow and indicates that the stall line may have a negative slope in this region. The occurrence of stall after the overshoot was found only in the low-speed region (below approximately 45-percent speed), and throughout the rest of the speed range the ramp and step increases in fuel flow gave results which appeared to be in good agreement.

The steady-state line and the surge, stall, and corresponding recovery lines are shown in relation to the compressor parameters of compressor pressure ratio and engine rotational speed as in figure 5. The ram pressure used in calculating the compressor pressure ratio in surge and stall was the mean ram pressure existing during the transient. The surge- and stall-recovery lines in figure 5 are well below the steady-state line except at low engine rotational speeds where the stall-recovery line is above the steady-state line. Although the surge- and stall-recovery lines are, in general, below the steady-state line, the acceleration at these recovery lines is positive except in the region of 75-percent speed where the acceleration approaches zero for the stall-recovery line.

At approximately 72-percent engine speed, the surge and the surge-recovery lines join and become the same line with decreasing engine speed. Although a hysteresis effect is present on a plot of fuel flow against engine speed, approximately the same pressure ratio exists at the two fuel flow values at constant engine speed in this region.

The path of an actual transient is represented on an expanded portion of the plot of compressor pressure ratio against engine speed (fig. 6). The transient into the surge region is shown in reference to the steady-state, surge, and surge-recovery lines. The pressure ratio at which recovery from surge was considered to occur, and, hence, the establishment of the surge-recovery line in the preceding figure, was arbitrarily picked as the lowest point just before which the engine recovered from surge (see fig. 3 point D). Figure 6 indicates, however, that the engine does not recover from surge as soon as the pressure ratio falls to the recovery line, but that the minimum points of the oscillations lie along the recovery line. Another line could be drawn which would be the upper envelope of the oscillations as shown in figure 6. The transient shown in figure 6 was initiated by using a step disturbance in fuel flow, and the engine recovered from surge before the fuel flow was cut back. Thus, the surge-recovery line represents a minimum pressure ratio for any fuel flow in the surge region. If, of course, the fuel flow were varied over a wide range of values during surge, some of the minimum points of the oscillations may lie above the recovery line.

As previously mentioned, transient operation of the engine in the range of low rotative speeds is limited by stall. A transient that passed through the stall region before encountering surge is shown in figure 7. The transient presented here is the result of a ramp increase followed by a decrease in fuel flow. As the fuel flow was increased, the 2725 stall line was approached and a stalled condition entered (point A) as shown by the drop in compressor pressure ratio at approximately 53-percent engine speed. As the fuel flow was increased still further, the engine operated deeper into the stalled region until surge occurred (point C). The fuel flow was then gradually decreased, and the engine recovered from surge (point D) and entered into the stalled region for a brief period before finally recovering from stall (point B) as shown by the sudden large increase in compressor pressure ratio. The final steady-state condition of the engine is not shown in figure 7.

The compressor map presented in figure 8 was obtained using two area-ratio settings of 1.1 and 0.88. Also shown on the compressor map are the surge and stall limits. The air flow at the surge and stall limits was obtained from the trace of the inlet dynamic pressure by determining the inlet dynamic pressure at the point that the engine encountered surge or stall. The constant-speed lines are shown as points on the surge line for the low-engine-speed range, since there is some question as to the manner in which these points are connected to the values along the stall line. In order to attain surge from a stalled condition, a large decrease in air flow must occur along with the decrease in compressor pressure ratio obtained in stall. Because the air flow was determined in a fairly crude manner, the results may not be quantitatively accurate but may be used qualitatively to show the trends on the compressor map.

Frequency of surge and stall. - Figures 2 and 3 show that, in general, two frequencies of oscillation exist, the high frequency encountered in stall and the low frequency encountered in surge. The high and low frequencies shown on these two traces were also found at several other altitudes. As shown in figure 2, the frequency encountered in stall was so high that at the chart speeds normally used in this investigation the frequency could not be calculated. Therefore, data were taken at ten times the normal chart speed in order to define the frequency during stall.

The frequency of surge was found to increase from approximately $6\frac{1}{2}$ to 10 cycles per second with decreasing compressor exit pressure over the range of compressor exit pressures encountered at each altitude. The data recorded at high chart speeds showed the frequency of stall to be about 37 cycles per second at 4700 rpm. Data were insufficient at the high chart speeds, however, to determine whether the frequency in this case was a function of some engine parameter. Stall appears to be confined to the compressor-inlet region and is probably the rotating type of stall as discussed in reference 1. In this type of oscillation, part of the compressor blades are stalled at the compressor inlet and the stalled region is propagated in the same direction as the rotor is turning but at a slower speed.

Altitude effect. - The curves to be discussed in this section are for a selected jet-exit area and ram pressure ratio. The surge and stall lines for altitudes of 15,000 and 35,000 feet have been combined and are presented as a limit line in figure 9 on a generalized plot of fuel flow against engine rotative speed. Figure 9 shows that up to at least 35,000 feet there appears to be only a small fuel-flow difference between the two generalized limit lines, and this fuel-flow increment is almost constant over the entire engine operating speed range. Only two altitudes are presented, and a wider variation in the generalized limit line could be expected at high altitudes because of changes in burner efficiency. A comparison of the two steady-state lines indicates that these lines do not generalize as well as the limit lines.

Another plot which involves compressor and engine variables (fig. 10) shows the relation between the limit and steady-state lines on a plot of fuel flow against compressor pressure rise. It must be remembered that for any given compressor pressure rise, the engine speed at high altitude is higher than that at a lower altitude at the steady-state and limit lines. At high engine rotational speeds, the limit lines at the high altitudes tend to intersect the limit lines at the low altitudes.

The surge, stall, steady-state, and surge-recovery lines for altitudes of 15,000 and 35,000 feet are shown on a plot of compressor pressure ratio against engine rotative speed (fig. 11). The surge and stall lines for both altitudes are practically the same and the difference shown is within the error of the data. Therefore, the difference shown in the limit lines for the two altitudes in figure 9 is probably due to changes in combustion efficiency. It will be noticed that at low speeds the steady-state, 35,000-foot line approaches the stall line.

Exhaust-nozzle-area effect. - The effect of the exhaust-nozzle area on the steady-state, surge, and recovery lines is shown in figure 12. At low engine rotational speeds, less fuel flow is required to stall or to surge the engine when the exhaust-nozzle area is in a more closed position. This figure indicates that at high engine rotative speeds, the engine requires more fuel flow before surge is encountered when the area is in a more closed position. The recovery lines have also shifted in a like manner and the stall-recovery line for the more closed area approaches the steady-state line.

Comparison of steady-state and transient surge lines. - During an earlier phase of the investigation of the engine, a steady-state determination of the surge line was accomplished by holding the engine fuel flow fixed and decreasing the turbine-inlet area by adjusting 2725
the first-stage turbine stator blades. A comparison of the surge lines obtained in a steady-state manner and the surge line obtained in a transient manner is made on a plot of compressor pressure ratio against engine rotational speed in figure 13. It can be seen that at least down to 70 percent of the rated engine rotational speed very little difference exists between the two surge lines, and the discrepancy could be attributed to the scatter of the data.

CONCLUDING REMARKS

An analysis of oscillograph traces obtained when an engine was forced off the steady-state operating condition by introducing sudden increases in fuel flow revealed two distinct types of flow breakdown in the compressor. For engine speeds below 67 percent of the rated value, a high-frequency oscillation of pressures occurred in the region of the compressor inlet that is attributable to localized stall; at higher speeds, or at very high fuel flows at somewhat lower speeds, a low-frequency oscillation was observed throughout the engine that is characterized by compressor surge. A hysteresis effect was found to exist; therefore, the fuel flow had to be below the surge or stall value in order for the engine to recover from surge or stall. Over a range of altitudes up to 35,000 feet, the surge and stall characteristics of the engine remained approximately the same. Very little difference existed between the surge line (compressor pressure ratio against engine rotational speed) obtained under transient conditions and that obtained under steady-state conditions by decreasing the flow area with an adjustable first-stage turbine stator.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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APPENDIX A

SYMBOLS

The following symbols are used in the figures:

A	cross-sectional area, sq ft
N	engine speed, rpm
P	total pressure, lb/sq ft abs
w_a	air flow, lb/sec
w_f	fuel flow, lb/hr
δ	pressure generalization factor, P/2116 (total pressure divided by NACA standard sea-level pressure)
θ	temperature generalization factor, T/519 (total temperature divided by NACA standard sea-level temperature)

Subscripts:

0	military static sea-level conditions
2	compressor inlet
4	compressor exit
n	exhaust nozzle
t	turbine exit annulus

APPENDIX B

TRANSIENT INSTRUMENTATION

Recording equipment. - Engine parameters were recorded during transients on six-channel, direct-inking, magnetic-penmotor oscillographs. Each channel of the recorders was driven by either a d-c or strain-analyzer type amplifier, depending on the parameter being measured. Strain-analyzer amplifiers were used with the sensing devices for pressures, fuel flow, and thrust, while d-c amplifiers were used with the sensing devices for speed, acceleration, temperature, and position. The frequency response of the penmotors in combination with either type amplifier is essentially flat over the range from 0 to 100 cycles per second. The oscillograph chart speed was 12.5 millimeters ($2\frac{1}{2}$ units) per second.

Timing marks were introduced on certain channels by removing the signals from these channels simultaneously, before or after a transient, by means of a switch (see fig. 3, beginning of run). These marks serve as a means of alining the traces from different recorders and for detecting slight variations in the length of individual pens.

Position indication. - The position of the exhaust nozzle, power lever, and fuel valve was indicated by a potentiometer attached in such a manner that the movable arm of the potentiometer was an indication of the position of the device. A d-c voltage was applied across the potentiometer so that a d-c voltage indicative of position appeared between the movable arm and either end of the potentiometer. For the transient indication, the initial level of the signal was cancelled by series addition of an adjustable voltage opposite in polarity to that of the signal. This is done since it is desired to record only the change during the transient. The signal is then applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is limited by that of the amplifier and recorder.

Turbine-inlet temperature. - Turbine-inlet temperature was measured by a number of sonic-type, shielded thermocouples placed at the turbine inlet and electrically connected in series. A switching arrangement was provided to bypass any of the thermocouples should they burn out or become grounded. The initial level of the signal was cancelled, and the signal was then applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is determined by the time constant of the thermocouples which is dependent upon the thermocouple material, wire size used, type of junction, and mass-flow conditions at the point of measurement. The thermocouples used had a time constant of approximately 0.6 second at sea-level, mass-flow conditions resulting in a frequency response which is essentially flat from 0 to 0.27 cycle per second at this condition.

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These same thermocouples were used for the steady-state indication. Relays were used to switch the thermocouples from the steady-state equipment to the transient equipment.

Turbine-exit temperature. - Turbine-exit temperature was measured by a number of 18-gage, chromel-alumel, butt-welded thermocouples placed at the turbine exit and electrically connected in parallel. The signal from the thermocouples was applied to a magnetic amplifier to increase the amplitude of the signal without the introduction of excessive noise or drift. The magnetic amplifier was followed by an adjustable voltage to cancel the initial level, a thermocouple compensator, and a d-c amplifier feeding one channel of a recorder.

The thermocouple compensator is an electric network which, when properly adjusted, compensates for the thermal lag of the thermocouple. A detailed discussion of the basic principles and circuits involved is given in reference 2. Use of this device allows the use of heavier thermocouple wire while obtaining faster response than could be ordinarily obtained with smaller wire. Methods for determining the time constant of thermocouples are given in reference 3.

The compensator was set by placing only one thermocouple in the circuit and then suddenly plunging the thermocouple from a cooled shield into the hot gas stream, effectively subjecting the thermocouple to a step change in temperature. The compensator was then adjusted until the temperature trace recorded as nearly a step as possible.

The frequency response of this circuit with the compensator properly adjusted is flat over the range from 0 to 5 cycles per second at sea-level, mass-flow conditions.

Engine speed. - An alternator on the engine provides an a-c voltage, the frequency of which is directly proportional to speed and varies from 300 to 800 cycles per second over the speed range normally encountered. This signal was used in connection with an electronic tachometer which was modified to give an accurate steady-state and suitable transient indication of engine speed.

The steady-state indication is provided by a counting circuit that counts the input frequency for a period of 1.2 seconds, which is accurately set by a crystal-controlled oscillator. This count is then presented on a neon-lamp display panel for a suitable length of time after which the process is repeated. Although the count is very accurate, unless the frequency is high in relation to speed, the speed cannot be accurately defined. Consequently, the alternator signal was first applied to two stages of full-wave rectification, which increased the frequency by a factor of four. With this modification, the steady-state speed indication was accurate to within 1 rpm.

The transient signal was obtained by modifying an existing meter circuit included in the instrument to provide a continuous indication of frequency and, hence, speed. A d-c voltage, proportional to speed, is produced by the modified meter circuit. After cancellation of the initial level, this signal was applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is limited by a filter circuit required in the modified meter circuit and is essentially flat over the range from 0 to 10 cycles per second.

Engine acceleration. - The transient acceleration signal was obtained by differentiating the speed signal with a simple RC circuit. The signal from the differentiating circuit was applied to a d-c amplifier feeding one channel of a recorder.

There is an inherent lag associated with the RC differentiating circuit which limits the frequency response to 2 cycles per second.

Air pressures. - Transient measurements of ram pressure, dynamic pressure at the engine inlet, compressor-exit pressure, turbine-exit pressure, and compressor pressure rise were made using standard, four element, strain-gage pressure pickups and strain analyzer-type amplifiers. A network in the analyzer provides a means of adjusting the initial output of the amplifier so that only the change need be recorded. The pressure pickups were mounted in a centrally located box designed to reduce the effect of engine vibration on the pickups.

The dynamic response of these circuits is a function of the diameter and length of the tubing used to transmit the pressure from the engine to the pressure pickup and the density of the air. Design of tubing size is outlined in reference 4. All tubing was experimentally tested and adjusted before installation to give a frequency response which is essentially flat from 0 to 10 cycles per second at sea-level conditions.

Fuel flow. - The transient indication of fuel flow was obtained by measuring the pressure drop across an orifice in the fuel line by means of a differential, strain-gage pressure pickup. The operation of the pressure pickup is the same in this case as for those used to 2725 measure air pressures. In order to obtain a sufficiently large pressure drop regardless of the fuel flow, the size of orifice used was made variable by means of a remotely controlled positioning system.

It should be noted that, for the fuel flow trace, the deflection is not a linear function of the fuel-flow change since the pressure drop across the orifice is proportional to the square of the fuel flow. When obtaining values from the fuel-flow trace, it is necessary to adjust for this effect.

The frequency response of this measuring system has not been determined.

Thrust. - The transient thrust measurement was obtained with a strain-gage mounted on a thrust link and a strain analyzer-type amplifier. The strain gage was bonded to a thrust link attached from the engine to the mount. The engine was supported in such a manner that the total force of the engine was transmitted to the mount through the thrust link.

The frequency response of the circuit to a change in the thrust link is limited by the recorder and amplifier, but the response of the entire system is dependent on the dynamics of the entire mounting system which has not been determined.

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TABLE I - INSTRUMENTATION

Measured quantity	Steady-state instrumentation	Transient instrumentation	
		Sensor	Range over which frequency response is essentially flat (cps)
Exhaust-nozzle area	Potentiometer attached to rack and gear assembly and connected in electric circuit to give indication on microammeter; microammeter reading converted to area	Control feedback potentiometer	0-100
Power-lever position	Potentiometer actuated by power lever and connected in electric circuit to give indication on microammeter; microammeter reading converted to degrees	Potentiometer connected to power lever	0-100
Turbine-exit temperature	24 Individual thermocouples connected to self-balancing potentiometer recorder	Six paralleled 18-gage, chromel-alumel, butt-welded thermocouples and electric network to compensate for thermocouple lag	0-5 at sea-level static when used with properly adjusted compensator
Turbine-inlet temperature	10 Individual traversing probes, sonic-type shielded thermocouples connected to self-balancing potentiometer recorder	Five sonic-type shielded thermocouples in series	0-0.265 at sea-level static
Engine speed	Modified electronic tachometer	Modified electronic tachometer	0-10
Engine acceleration	Calibration obtained from transient speed traces	Modified electronic tachometer and differentiating circuit	0-2
Ram pressure	Water manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Dynamic pressure at engine inlet	Water manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Compressor-exit total pressure	Mercury manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Turbine-exit total pressure	Alkazene manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Thrust	Scale	Strain gage mounted on strain link attached to forward engine suspension	0-100
Fuel flow	Rotameter	Aneroid-type pressure sensor, with strain-gage element, connected to measure pressure drop across variable orifice in fuel line	Undetermined

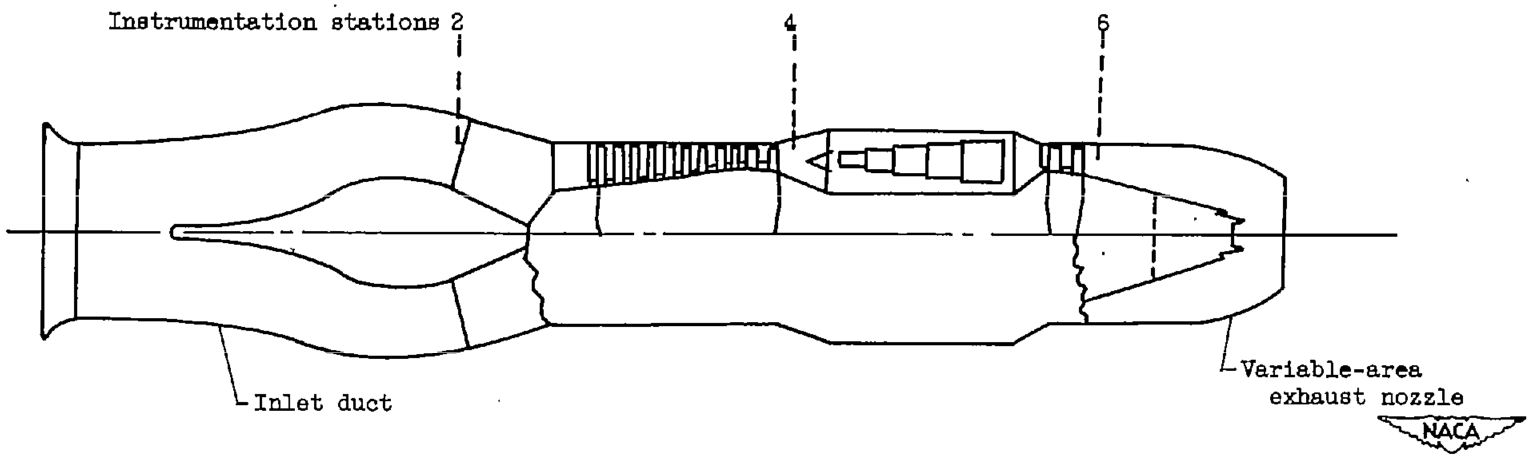

Figure 1. - Engine schematic diagram illustrating inlet ducting and instrumentation stations.

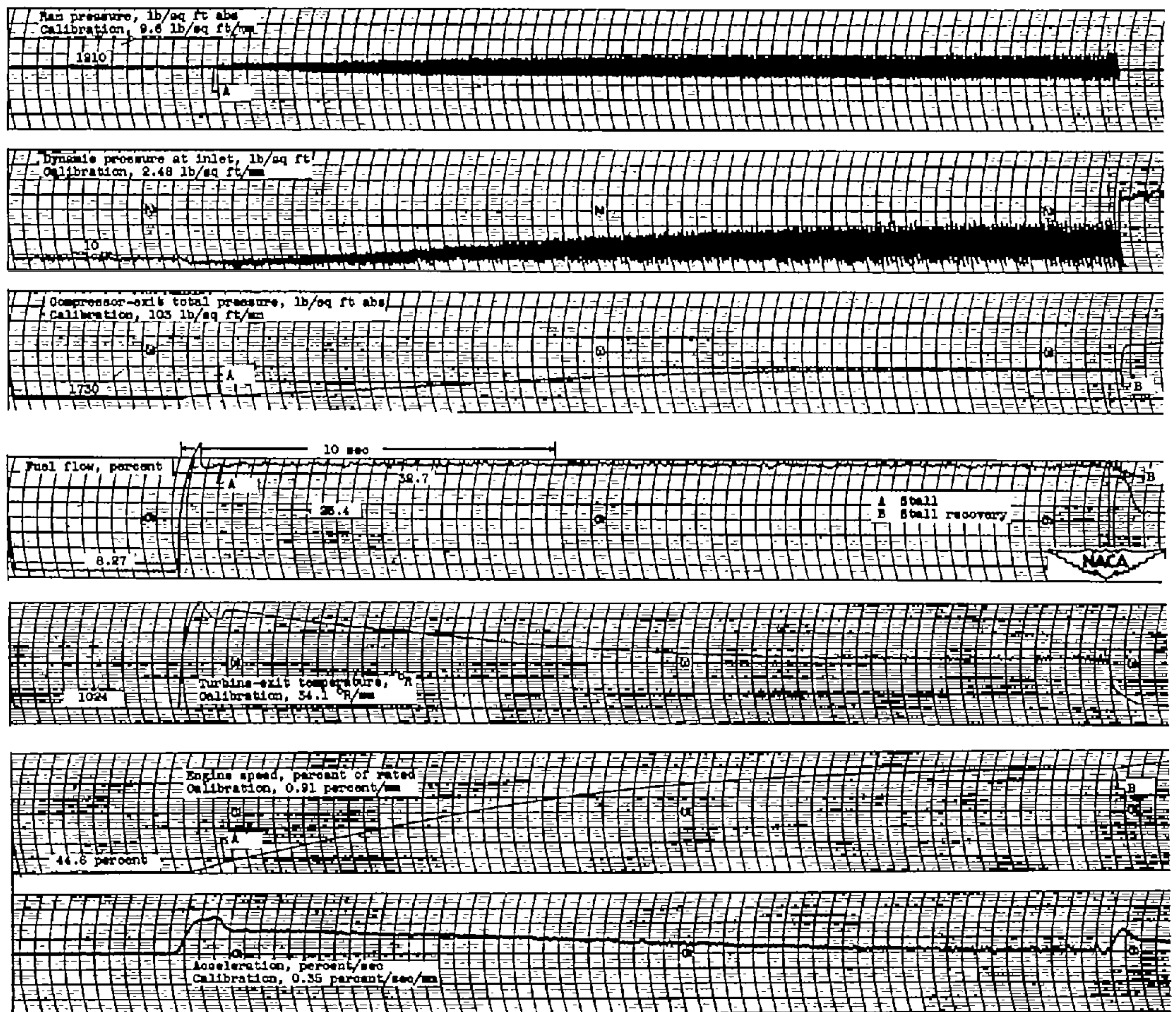

Figure 2. - Response of several engine variables to step increase in fuel flow illustrating high-frequency stall encountered at low engine rotational speeds.

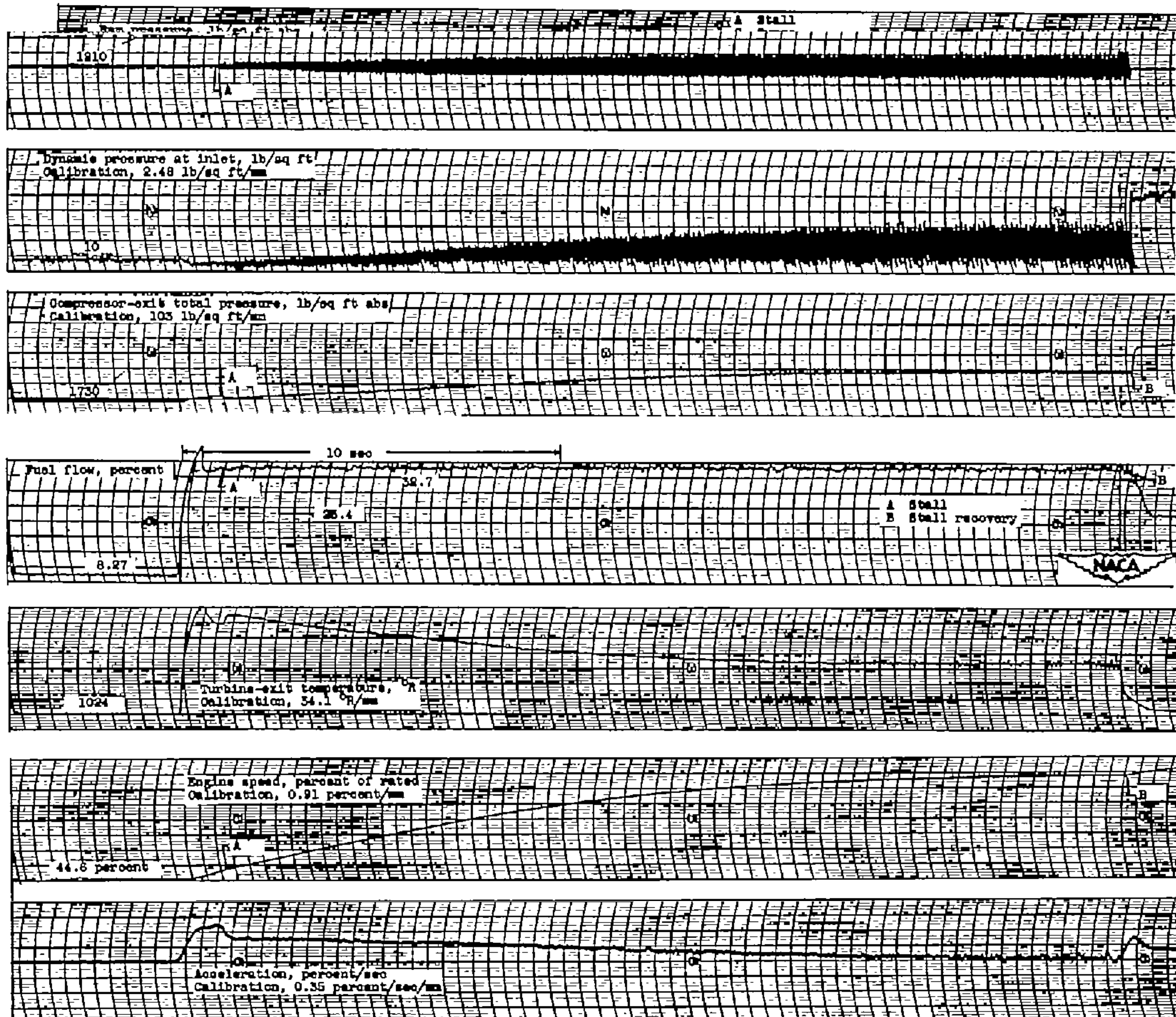

Figure 2. - Response of several engine variables to step increase in fuel flow illustrating high-frequency stall encountered at low engine rotational speeds.

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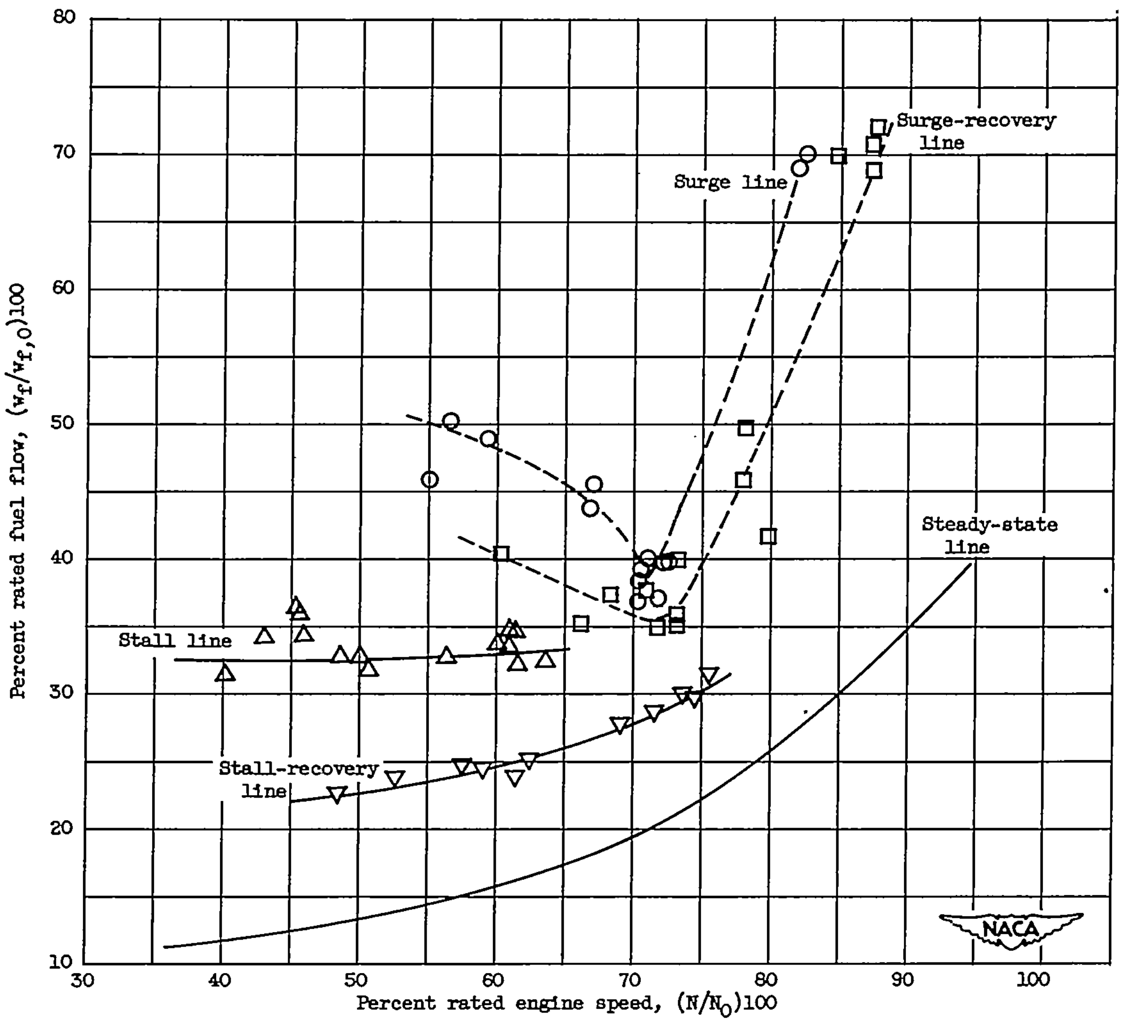

Figure 4. - Variation of fuel flow with engine speed illustrating steady-state, surge, surge-recovery, stall, and stall-recovery lines. Altitude, 15,000 feet; ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

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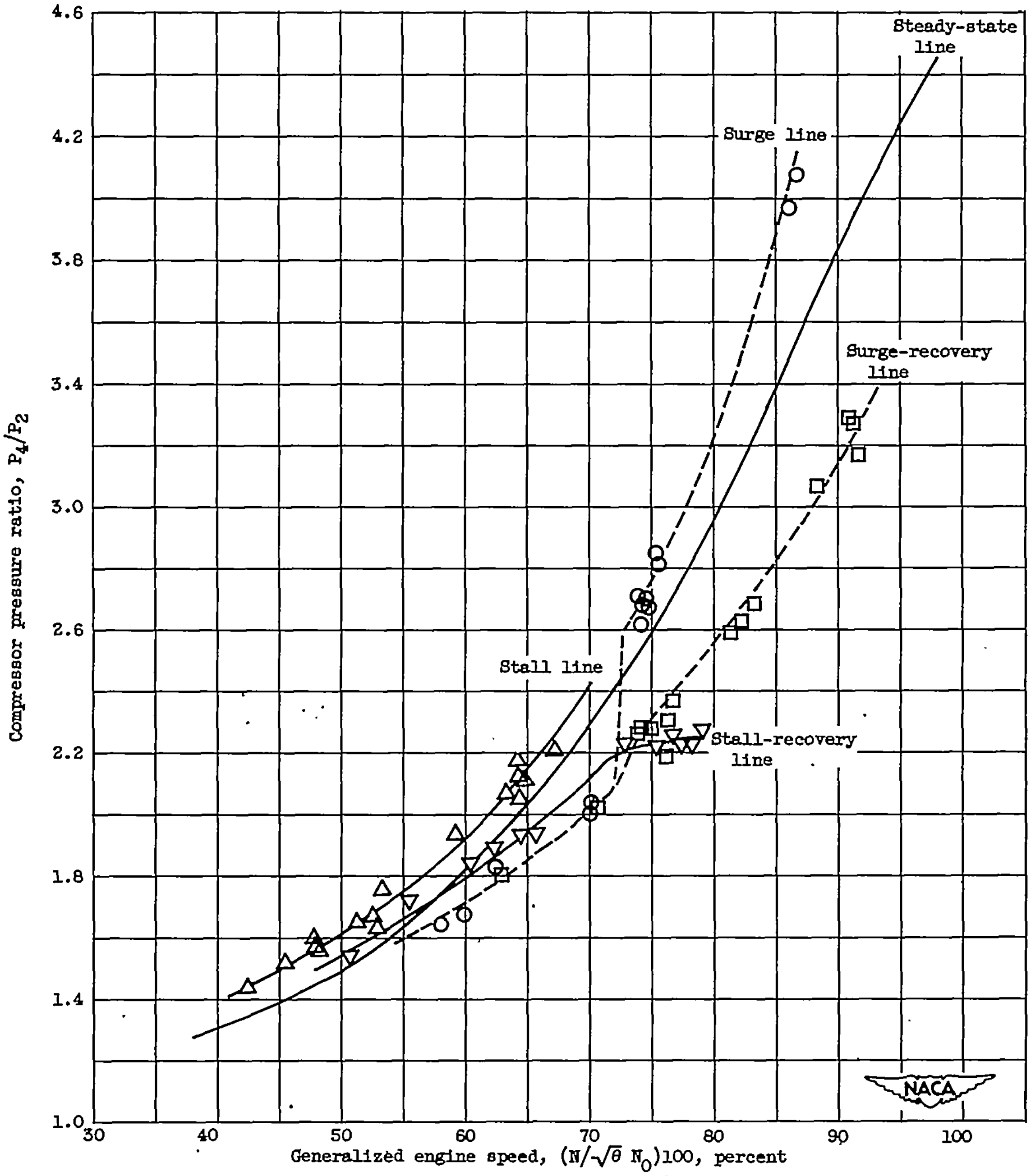

Figure 5. - Variation of compressor pressure ratio with generalized engine speed illustrating steady-state, surge, surge-recovery, stall, and stall-recovery lines. Altitude, 15,000 feet; ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

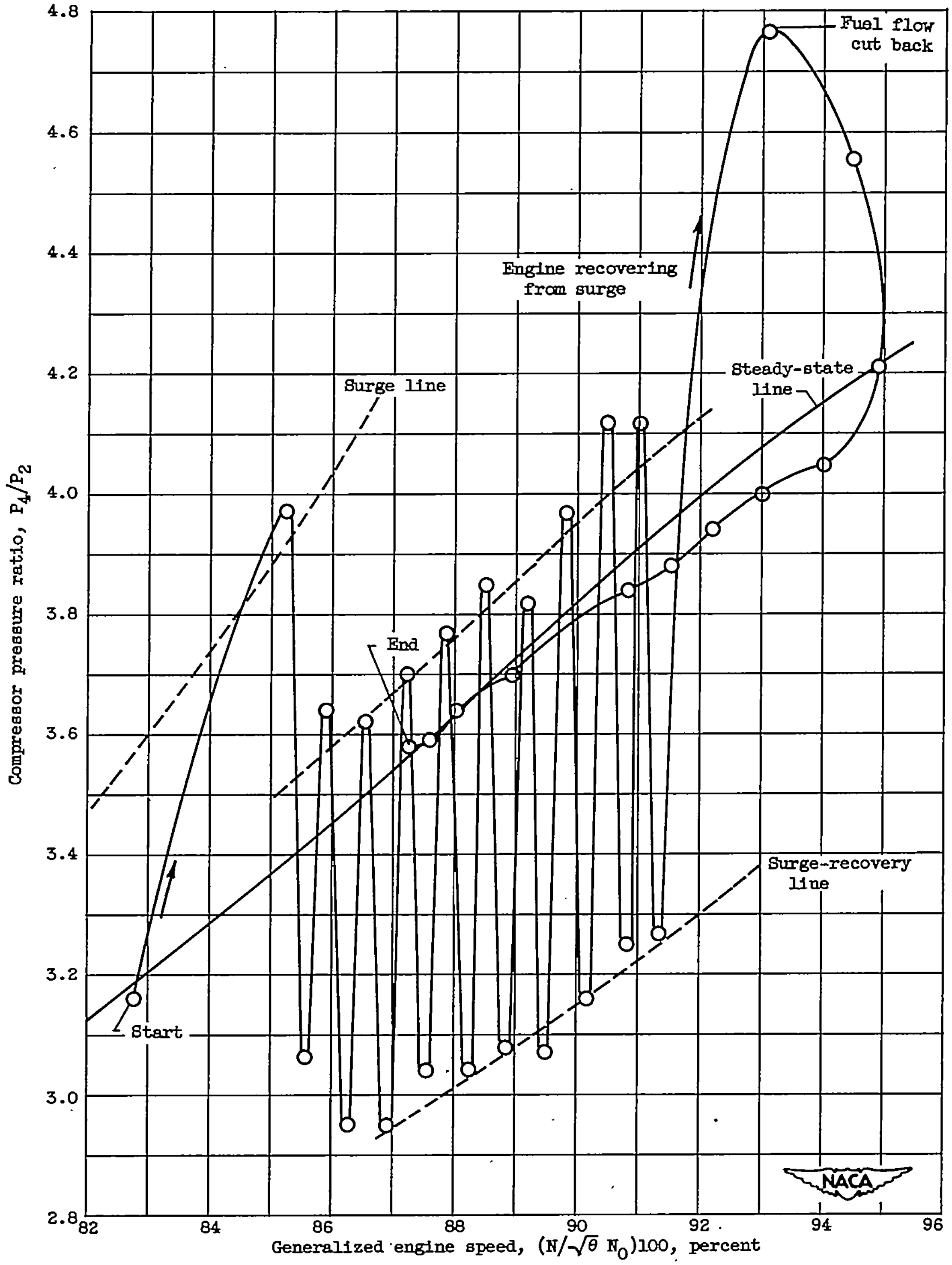

Figure 6. - Variation of compressor pressure ratio with generalized engine speed showing transient into surge and subsequent recovery of engine from surge. Altitude, 15,000 feet; ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

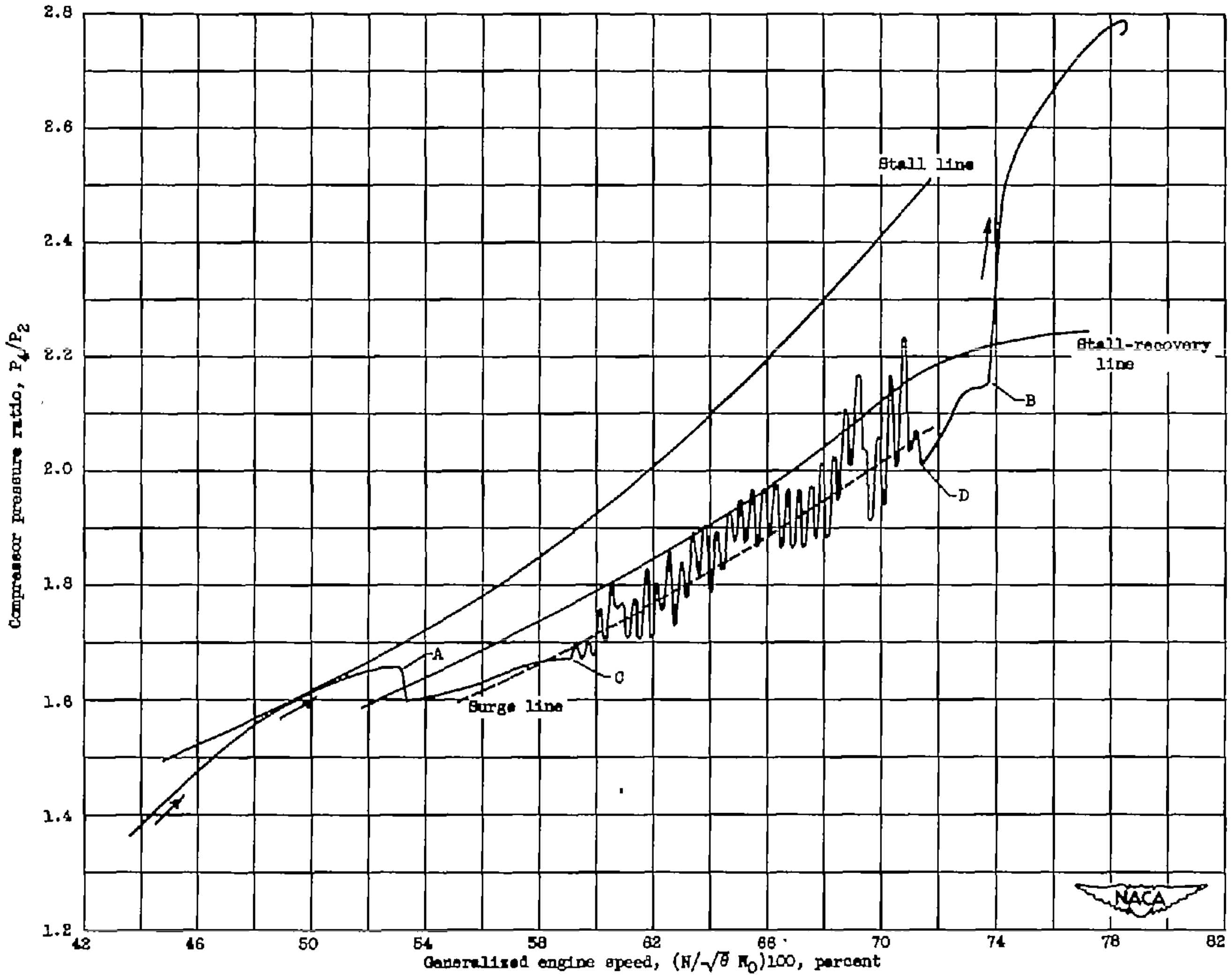

Figure 7. - Variation of compressor pressure ratio with generalized engine speed showing transient into stall and surge and subsequent recovery of engine from stall. Altitude, 15,000 feet; ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

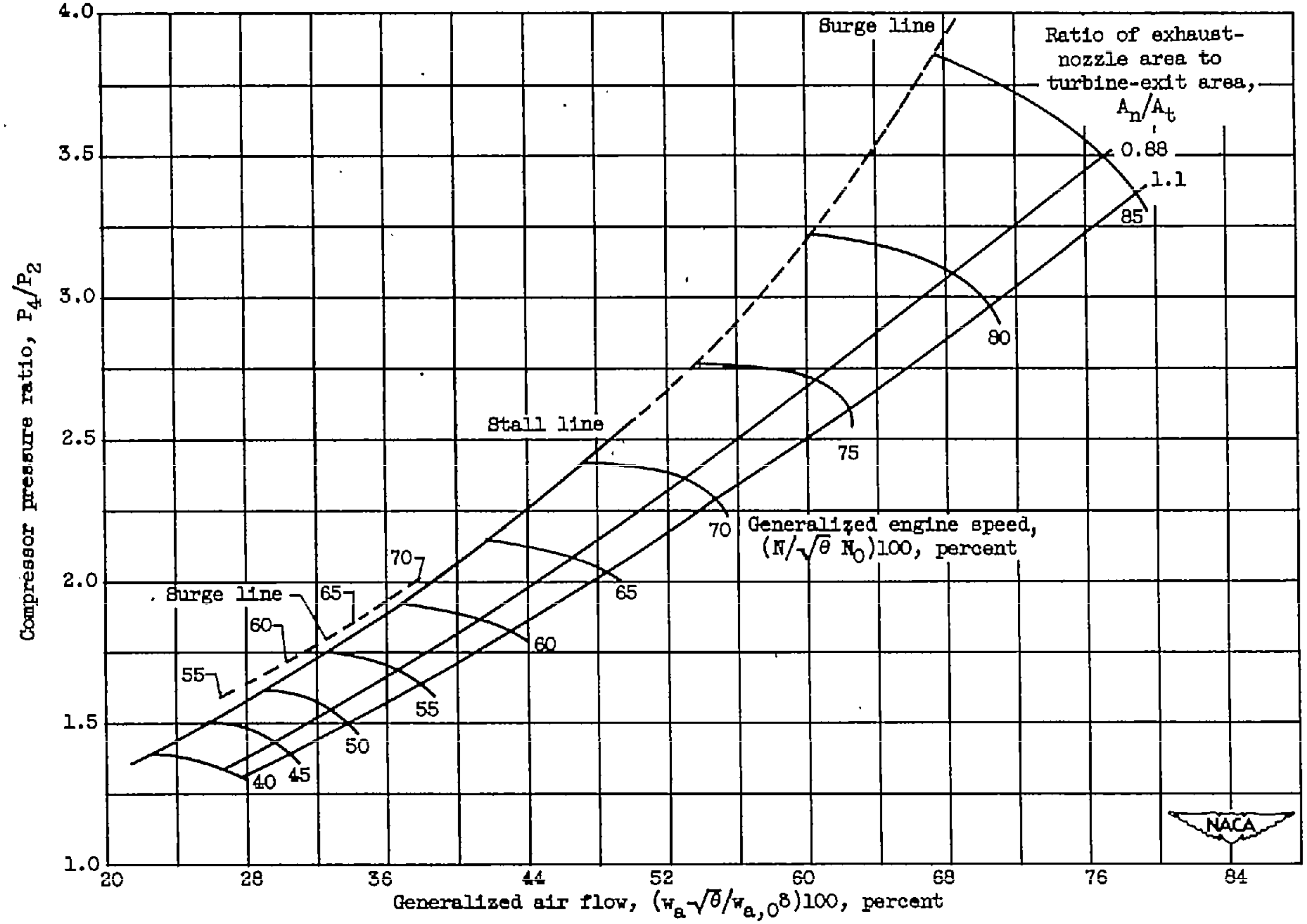

Figure 8. - Compressor map showing surge and stall lines, constant-speed lines, and steady-state lines for two ratios of exhaust-nozzle area to turbine-exit-annulus area. Altitude, 15,000 feet; ram pressure ratio, 1.02.

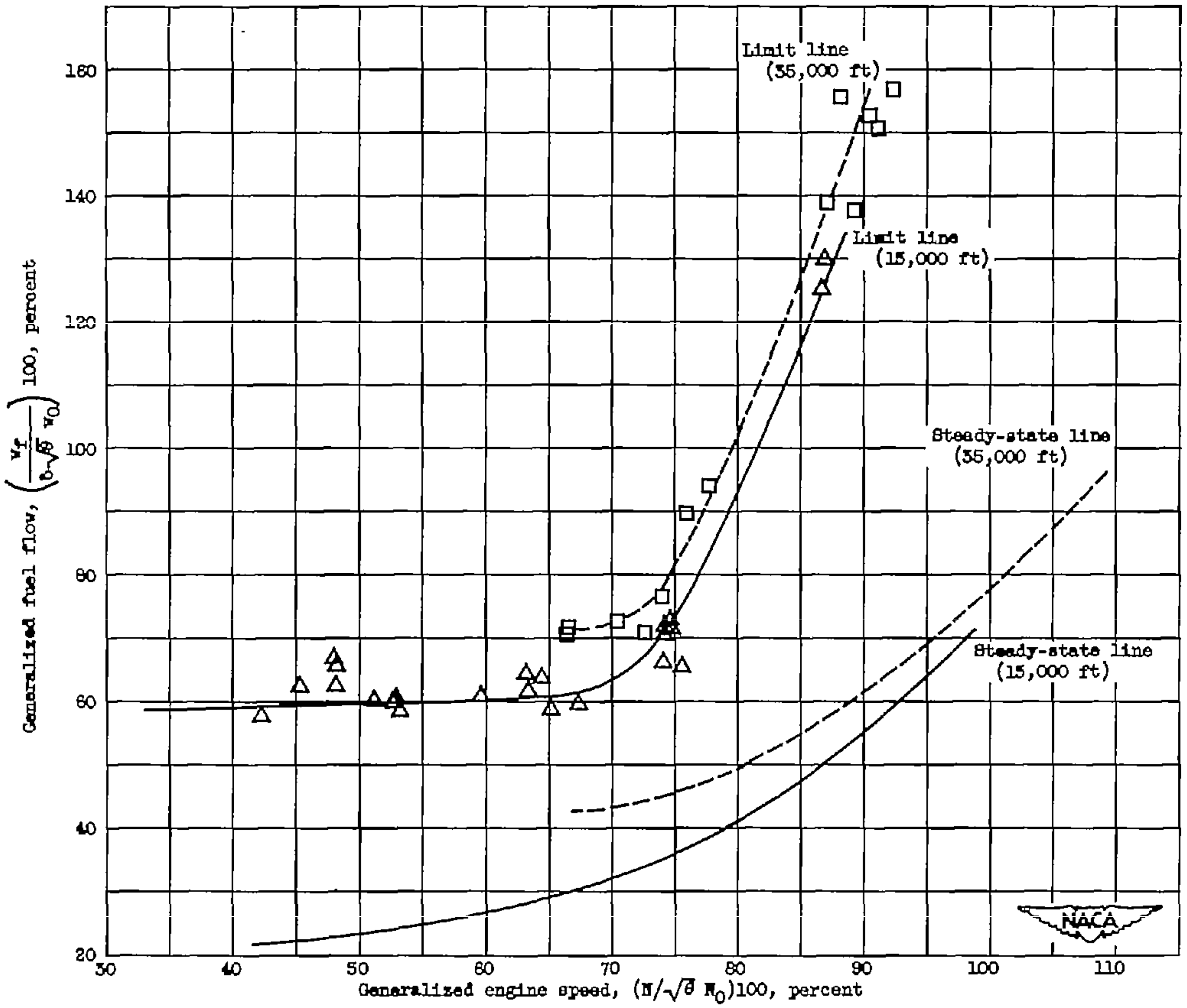

Figure 9. - Effect of altitude on combined surge and stall line (limit line) and steady-state line. Ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

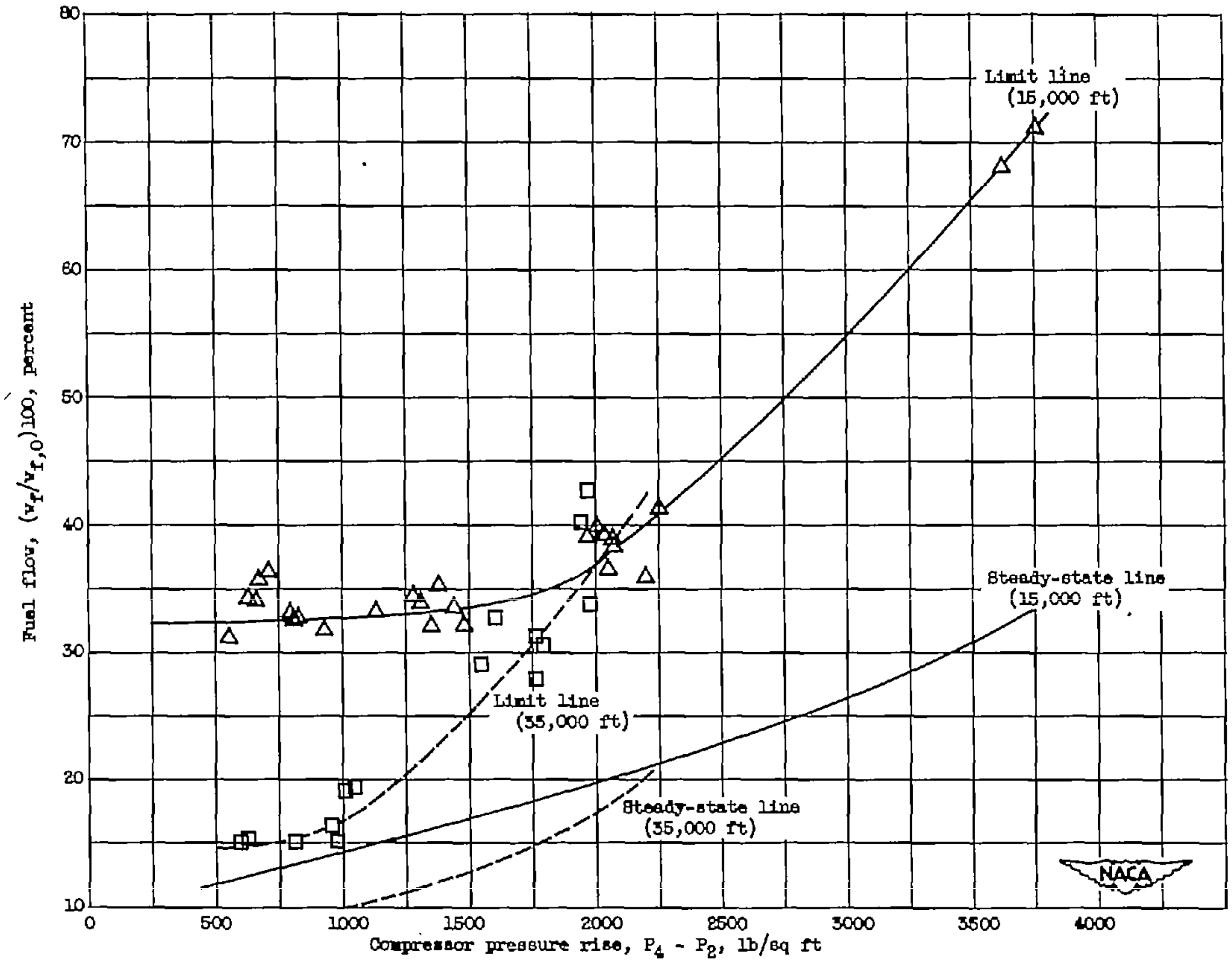

Figure 10. - Variation of fuel flow with compressor pressure rise at combined surge and stall line (limit line) and steady-state line illustrating effect of altitude. Ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

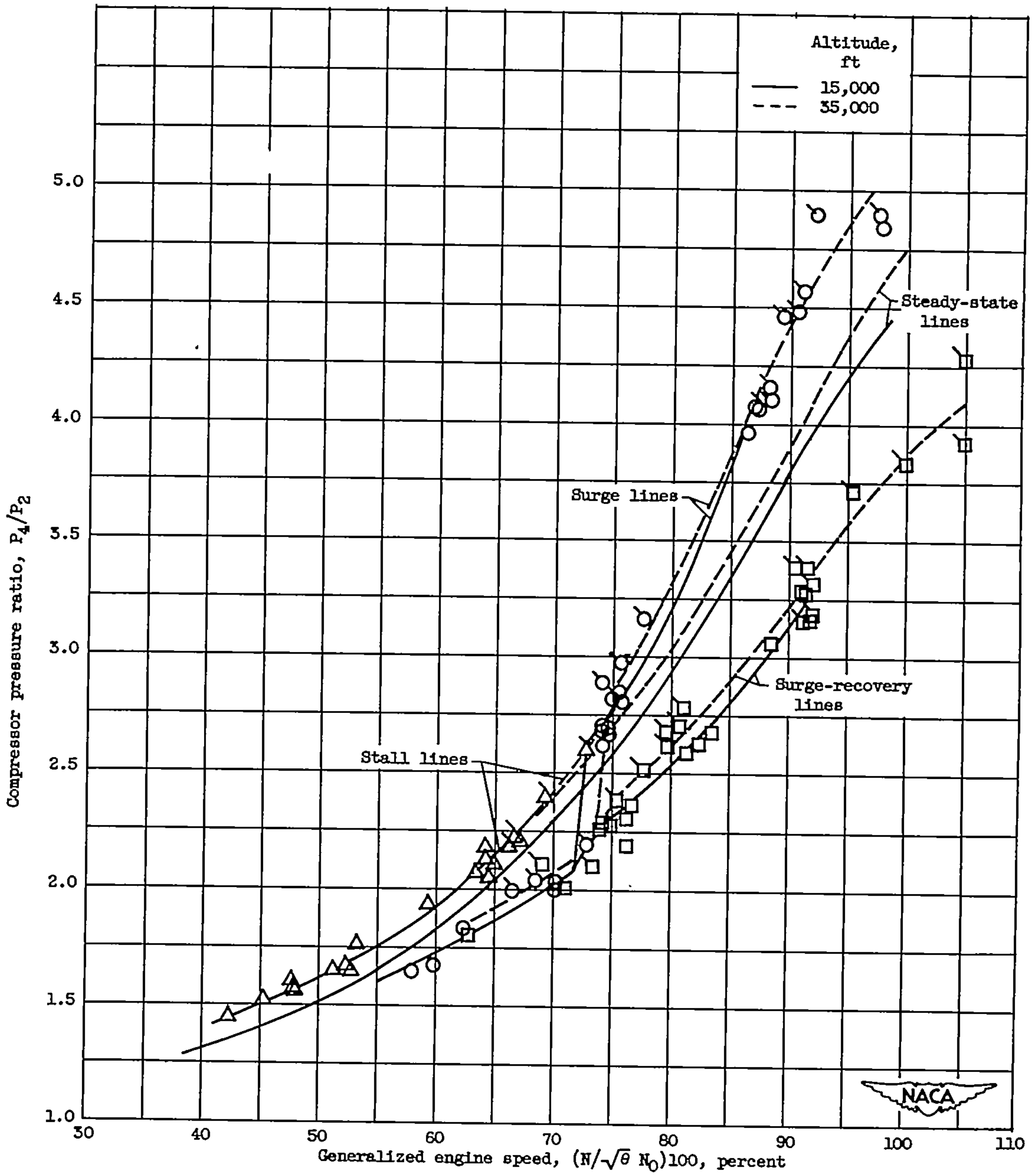

Figure 11. - Effect of altitude on surge, surge recovery, stall, and steady-state lines. Ram pressure ratio, 1.02; ratio of exhaust-nozzle area to turbine-exit-annulus area, 1.1.

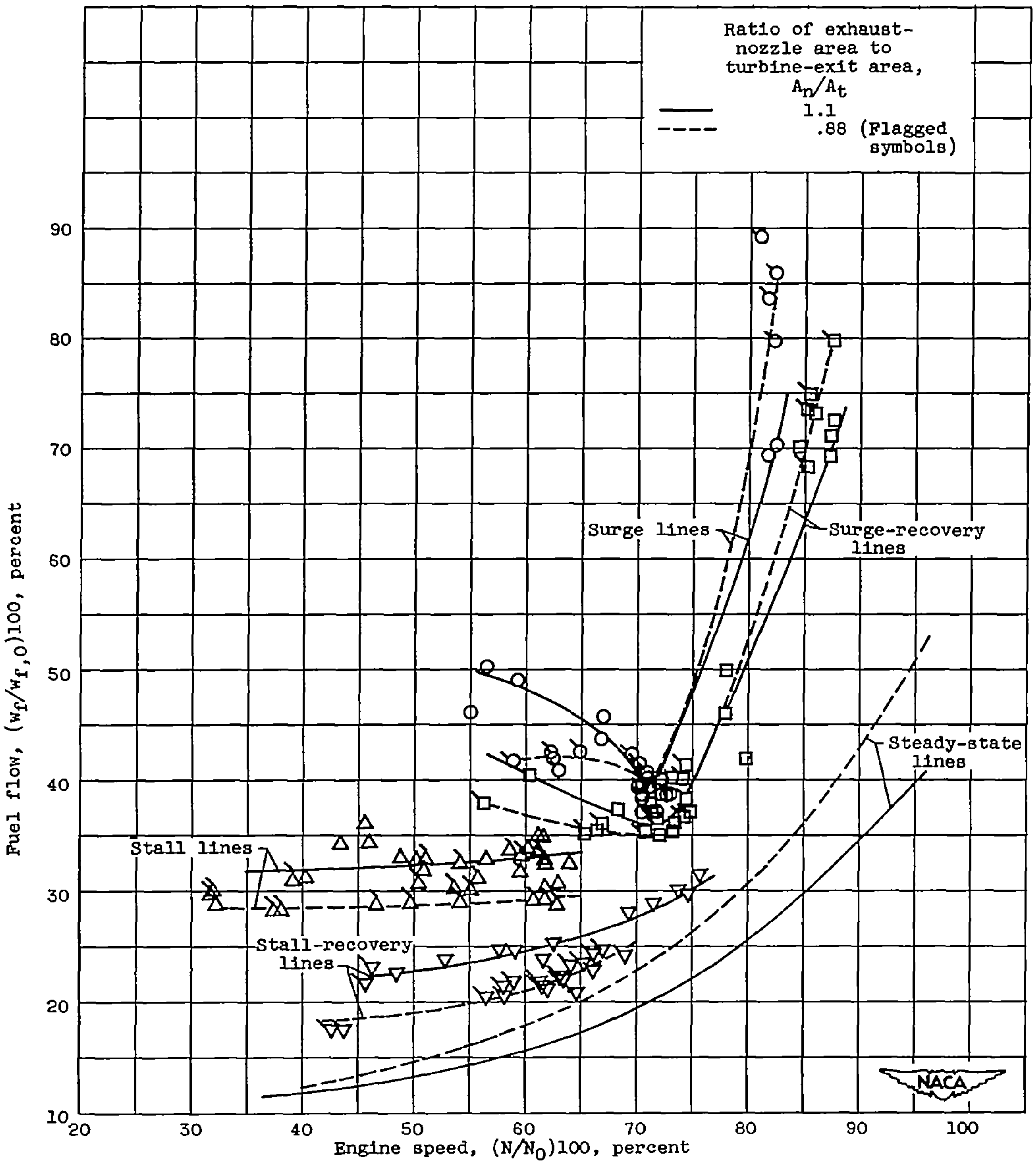

Figure 12. - Effect of exhaust-nozzle area on amount of fuel required at surge and stall and corresponding recovery lines and at steady-state line. Altitude, 15,000 feet; ram pressure ratio, 1.02.

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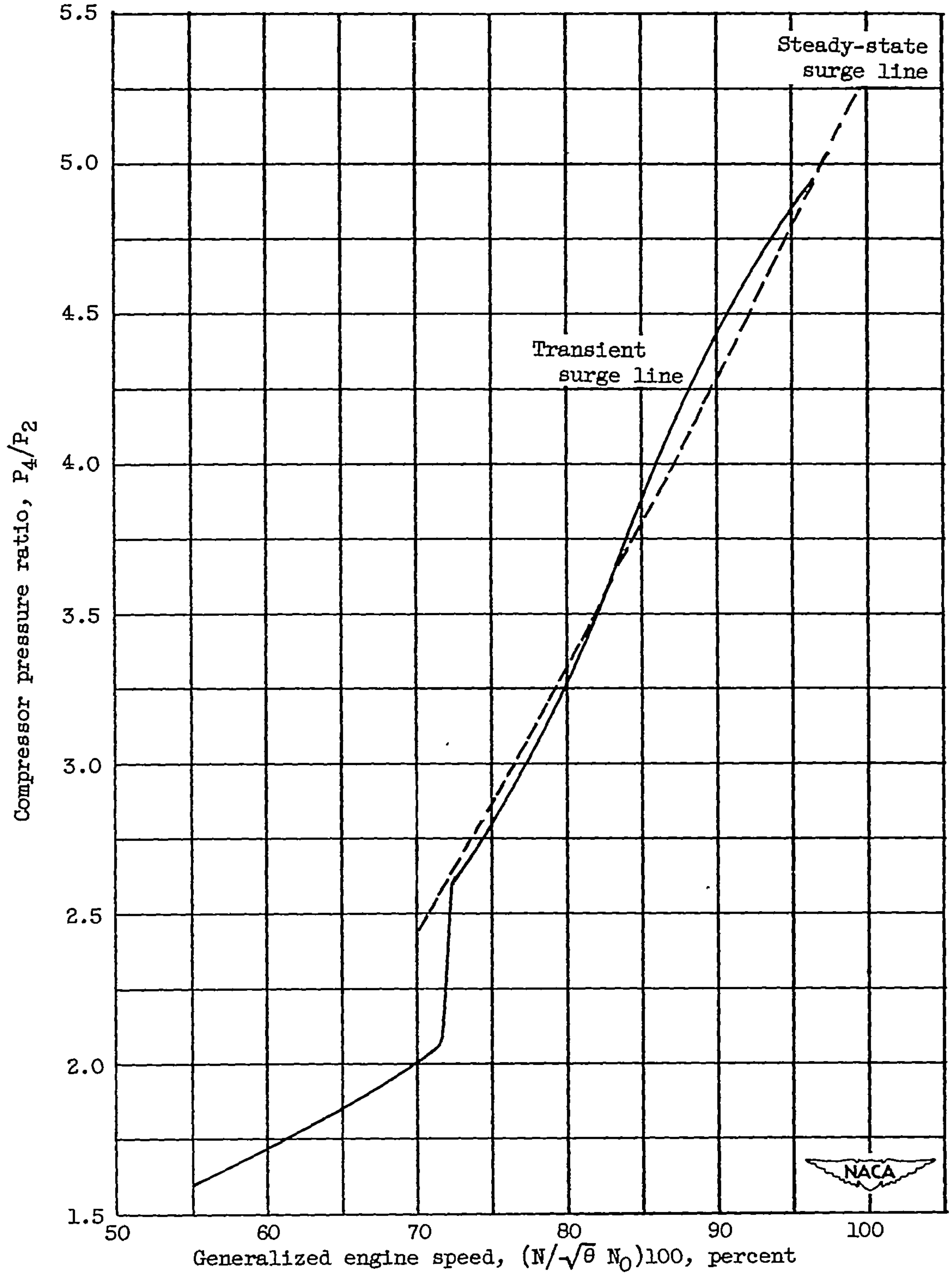

Figure 13. - Comparison of surge line obtained in steady-state and surge line obtained from fuel-flow transients.